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Space Guidance Analysis Memo # 7-69

TO: Distribution
FROM: Allan Klumpp and Nick Pippenger
DATE: August 27, 1969
SUBJECT: How to Land Beside Surveyor 3 on Apollo 12

I. SUMMARY

An objective of Apollo 12 is to land between 500 and 1500 ft. of the Surveyor 3 spacecraft which has been sitting on the moon since the end of April, 1967. The plan is to retrieve certain optical and other parts of the Surveyor spacecraft to determine how these withstand $2\frac{1}{2}$ years in the lunar environment. A minimum separatio of 500 ft. is desirable to minimize impingement upon the Surveyor by particles thrown by the exhaust of the descending LM.

Because the Apollo 11 LM missed the intended landing spot by some 23,000 ft., many people doubt Apollo 12 can land within such a close range of Surveyor 3. Others of us believe it can using the following approach:

1. The Mission Control Center Houston (MCC-H) must accurately compute the location of the crater in which the Surveyor rests using downlinked landmark tracking data from the Command Module Optics. The surveyed location of Surveyor will be referenced to the MSFN determination of the CSM-LM orbit to an accuracy of 900 ft. 3 sigma downrange and crossrange. (Preliminary estimates by Emil Schiesser, MSC.)

2. Minimize the uncertainties in the LM orbit resulting from undocking, separation, and DOI by stringent procedures (Ref. 1). Although there is no estimate of how accurately this can be done, it should be possible to do several times better than on Apollo 11 where no such effort was made.

3. Following DOI, telemeter the DOI residuals to MCC-H. These residuals are subtracted from the DOI velocity increment supplied by MCC-H to determine the velocity increment actually imparted during DOI and the corresponding LM state vector following DOI, called SV_2. This and the

corresponding landing site RLS_2 are uplinked to the LM as soon as possible following acquisition of signal just prior to PDI.

4. Between DOI and PDI the LM position is determined to an accuracy of 3000 ft. 3 sigma in the cross range direction from tracking on previous orbits, and 3000 ft. 3 sigma in the downrange direction from MSFN ranging and the Lear processor. (Emil Schiesser, preliminary.) Unfortunately there is insufficient time to correct the onboard LM state vector using this data, but the data is used to determine the onboard LM state vector error, and the compensating landing site displacement correction is computed and voice linked to the LM Pilot by at least 8 minutes prior to PDI. The LM Pilot corrects the landing site using the new technique described in Ref. 2 and then calls the landing program P63. Because the correction is made before the Ignition Algorithm is processed, the guidance system will ignite the engine at the corrected time and the propellant cost of this correction is therefore zero. The landing site displacement correction eliminates all previously acquired errors except for the error in determining the landing site location by CSM tracking. The PNGCS may accumulate errors during the braking phase of 630 ft. downrange due to a 3 sigma scale factor error of .00045 and 4200 ft. crossrange due to a 3 sigma platform alignment error of 3 milliradians. The velocity error at PDI is not included because it is assumed this error will be detected by the Lear processor and corrected by the landing site displacement correction made prior to starting the ignition algorithm. These PNGCS errors are preliminary, they include only the sources expected to predominate. The RSS of the three remaining errors (the tracking error at PDI, the landing site error, and the PNGCS error) is 3195 ft. downrange, 5239 ft. crossrange, 3 sigma, so that in the absence of further corrective action the LM would land within this range of the targeted landing point.

5. The geometry for the Lear processor improves as the LM approaches PDI. Therefore, it may be possible to voice link an additional landing site displacement correction to the LM Pilot during the early portion of the braking phase. Providing this correction is made before throttle recovery, the propellant cost is very small, a fraction of the cost of landing site redesignation during the approach phase (see section III. of this memo). However, because of the other demands on the crew during the braking phase, there is no guarantee this additional landing site displacement can be accomplished, and the capability to land within the specified range of Surveyor 3 is not dependent upon it.

6. From training in terrain recognition using maps and photos presently being compiled at Houston, the LM Commander will be able to identify the intended landing point at the very beginning of the approach phase. This is a critical assumption. Assuming the additional landing site displacement correction during the braking phase is not accomplished, the errors of item 4 above remain to be corrected by landing site redesignation.

The targeted landing point will be biased short of the intended landing point by the amount of the downrange error, and the approach phase trajectory will be redesigned by techniques described in section II of this memo to provide at least twice this redesignation capability in the forward direction. It is not feasible to provide any substantial redesignation capability in the backward direction. Techniques for using the Landing Point Designator (LPD) are described in section IV and References 4 thru 6.

II. TRAJECTORY DESIGN

The Apollo 11 descent trajectory provided very little redesignation capability compared to preceding trajectories (Ref. 3). The Apollo 11 trajectory was designed to the direction of Neil Armstrong who stated that we could consider one redesignation increment to be the maximum he would issue. Indeed he did issue only one, and he stated during the debriefing it was unintentional. Neil's single recommendation was to have more time in the region between 300 and 500 ft. altitude. With the Apollo 12 objectives we must also recover a considerable redesignation capability compared to Apollo 11.

A preliminary prototype trajectory for Apollo 12 has been designed which provides substantially increased redesignation capability and flares out in the 500-300 ft. region to provide a considerable increase in the time available for final assessment of the landing point. This trajectory has been flown by the prime crew Conrad and Bean and the backup crew Scott and Irwin on the LMS at the cape. They have successfully flown at least 9000 ft. past the initially targeted landing point with this trajectory using a combination of LPD and P66.

The following concepts should be considered for the Apollo 12 trajectory design; most are incorporated in the preliminary prototype.

1. The terminal pitch angle of the braking phase may be displaced slightly from optimum to allow visual acquisition of the landing site before the start of the approach phase. Early acquisition would permit early redesignation and minimize the net propellant cost.

2. We should consider shortening the throttle control duration and increasing the throttle recovery criterion and the terminal throttle position of the braking phase.

3. The initial point in the approach phase should be at a range not exceeding the maximum at which the landing site can be identified, and the approach phase duration should be such as to produce the maximum permissible throttle level at the start of the approach phase.

4. The approach phase should be targeted to a terminal altitude in the region of 250 to 300 ft. altitude, with 15fps downward and 85 to 95 fps forward velocity at 500 ft. altitude. This produces a substantial flare of the trajectory in the 500-300 ft. region and substantially increased time for final assessment of the landing site. Also, with 250 ft. terminal altitude, any droop due to long redesignation is relative to 250 ft. and the minimum altitude is not dangerous. However, this design essentially precludes landing with P65 because of the propellant cost of the prolonged vertical descent from the approach phase terminus; this is no loss, there was never any intention to use P65.

5. This type of trajectory retains to the end of the approach phase a geometry favorable in every respect for site redesignation. The loss of redesignation capability prevented the Apollo 12 crews from fully utilizing the capability of the automatic system on the LMS. With GAINAPPR set to zero, there is no need to end redesignation capability, and it should be retained all the way to the end of the approach phase.

III. LANDING SITE DISPLACEMENT

Starting with Apollo 12, a new three component Noun 69 will allow the crew to modify the landing site in platform coordinates, LAND. This vector is initialized from RLS (the landing site in selenographic coordinates) when P63 is selected and is used by both the ignition algorithm and the guidance equations. We will describe the cost in fuel (δv) for positive downrange displacements ($\delta z > 0$); this cost may be put into terms of hover time by using the rule 5 ft/sec. $\delta v \simeq 1$ second of hover time.

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The two most important events influencing the total δv usage are ignition and throttle recovery. The time of ignition is determined by the ignition algorithm at least eight minutes before ignition. The time of throttle recovery is determined by the guidance equations, at essentially the time it occurs. In each case the time determination is based on the value of the landing site vector (LAND) when the

determination made. If LAND is changed after the determination is made, a price must be paid for the use of a poor decision in the overall policy. The numbers quoted for the following cases are based on a trajectory similar to what will probably be designed for Apollo 12.

Case 1 If the displacement is incorporated before the ignition algorithm is run, then no important decisions are based on the old value of LAND, and no price is paid.

Case 2 If the displacement is incorporated after the ignition algorithm is run, a wrong ignition time will have been used. For forward displacements of up to 20 K ft. the cost of this is 1.6 ft/sec of δv per K ft. of δz.

For a given set of braking phase targets, and a given time of ignition, optimum throttle recovery time is a function of the landing site. The time chosen by the system reflects the relative importance of the following three criteria (in order of decreasing importance):

1. The full throttle region must be long enough to allow the craft to decelerate to zero velocity before reaching the landing site.

2. The throttle control region must be long enough to soak up engine dispersions and still meet the braking phase targets.

3. Throttle down should be as late as possible to minimize propellant consumption.

This optimum time is up to 16 seconds before the nominal throttle recovery time for forward displacements up to 20 K ft. It is not, of course, the time at which the throttle would recover had the ignition time been correct.

Case 2a If the displacement is incorporated before this optimum throttle recovery time, throttle down will occur at the optimum time. During the entire interval between the running of the ignition algorithm and optimum throttle recovery, the cost of a forward displacement increases less than 10 percent.

Case 2b If a forward displacement is incorporated after this optimum time, throttle down will occur late, and a price of 0.1 ft/sec δv per second of lateness per K ft. of δz must be paid, in addition to the price for mistiming the ignition. In this case, fuel consumption must be compromised in order to allow sufficient time under throttle control. If such a displacement is incorporated between the optimum throttle down time and the nominal throttle down time, it will cause immediate throttle recovery.

In the case of a backward displacement optimum throttle down will be later than the nominal throttle down; incorporation of the displacement during the intervening interval will cause the throttle to return to full thrust temporarily. In this case duration of the throttle control region must be compromised in order to decelerate to the targets; there is a saving in fuel but smaller engine dispersions are tolerable.

The costs for forward displacements at various times are summarized in Fig. 1.

IV. LANDING SITE REDESIGNATION

Quite a bit has been written on LPD accuracy and operation (Ref. 4 thru 8). There are several adverse effects in LPD operation which must be overcome, and some of the procedures proposed are quite cumbersome. The adverse effects are listed below followed by a procedure which is simple and effective.

1. LPD mechanical alignment error of about 1° relative to the navigation base.

2. Alignment error of the eye relative to the LPD of about $1/2^{\circ}$.

3. Terrain slope and IMU bias produce an additional error which act similarly to the bias errors mentioned above.

4. The LPD angle is approximately $1\frac{1}{2}$ seconds old at the time that it is displayed, probably 3 seconds old when first heard by the commander.

5. The line of site gradually rises in the window during the first half of the approach phase by as much as $1/3^{\circ}$/ second, and the autopilot deadband allows additional attitude motion. These, combined with the delays in display and call-out, produce an additional bias-like error of as much as 1^{0} on top of a small oscillatory error.

Fortunately, there is a simple way to distinguish between the above bias-like errors and an error in the position at which the spacecraft will land (landing point error). The above effects produce roughly constant and oscillatory angular error components in the LPD display, whereas a landing point error produces a divergent angular error. From Fig. 2 the differential equation for the error due to landing point error is approximately

$$\frac{d\epsilon}{dt} = \epsilon \frac{v}{r_I}$$

where ϵ is the angular error, v is the speed along the LOS, and r is the slant range. The decreasing throttle profile makes v / r roughly constant, yielding an angular error which diverges roughly exponentially with a time constant of about 50 seconds at the start of the approach phase and speeding up to about 20 seconds at 500 ft. altitude.

Figure 3 illustrates the landing site redesignation procedure. The thresholds permit the bias and oscillatory errors to be ignored, whereas any divergent error will be corrected. Commands are issued to correct all of the observed error rather than merely the excess over the threshold. This policy compensates for the divergent growth during the interval the correction is being applied. The policy of ignoring the elevation (downrange) error (unless the number of elevation commands exceeds the number of azimuth commands) avoids issuing doubtful elevation commands.

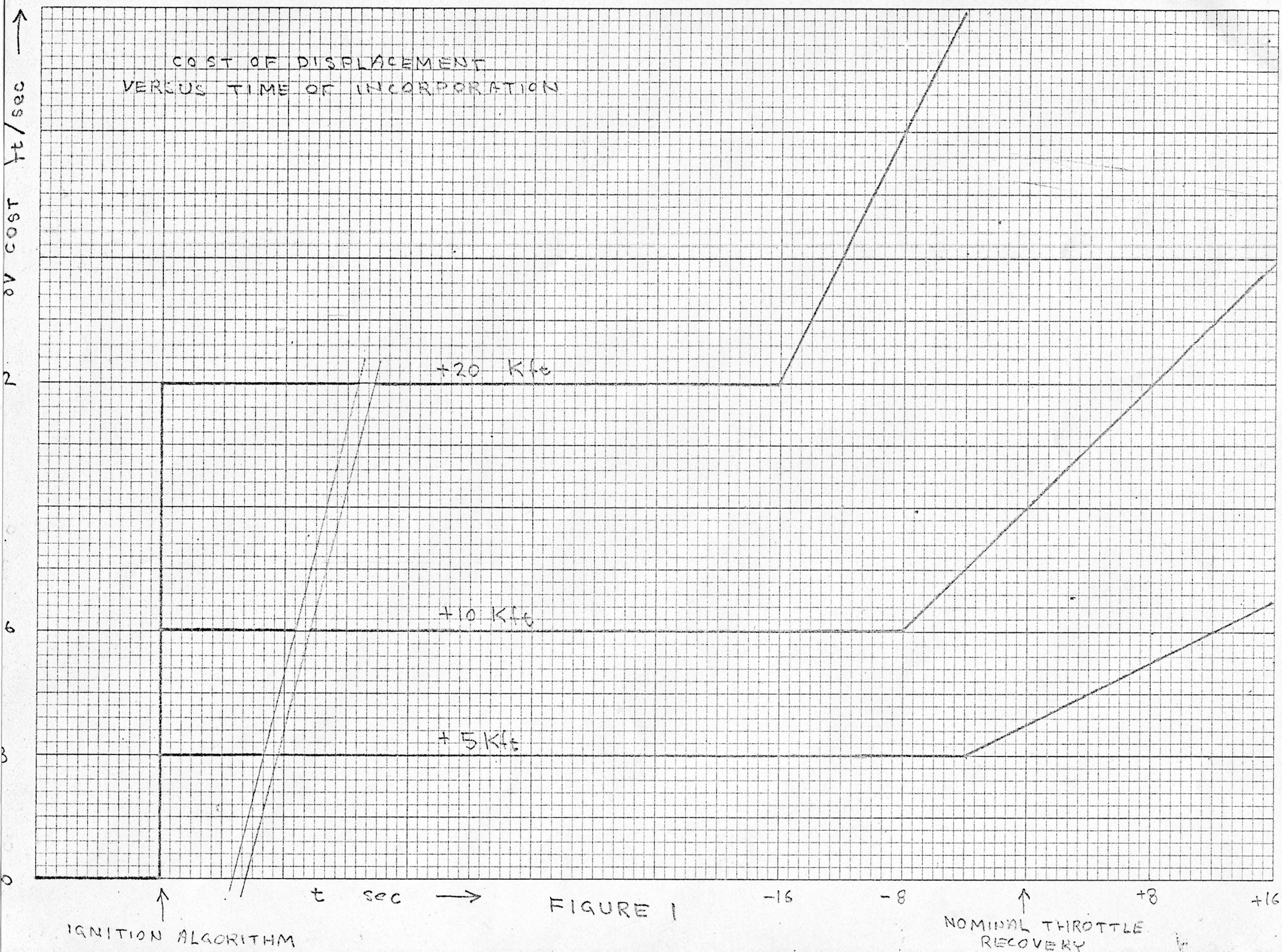

COST OF DISPLACEMENT
VERSUS TIME OF INCORPORATION
ΔV COST ft/sec
2
6
8
0
+20 Kft
+10 Kft
+5 Kft
t sec
-16
-8
+8
+16
IGNITION ALGORITHM
NOMINAL THROTTLE RECOVERY

FIGURE 1

$r_c = h \sec\alpha$ SLANT RANGE TO COMPUTED SITE

$dr = h \sec\alpha \tan\alpha \, d\alpha = \varepsilon h \sec\alpha \tan\alpha$

$r_I = h \sec\alpha + \varepsilon h \sec\alpha \tan\alpha = r_c \,(1 + \varepsilon \tan\alpha)$ SLANT RANGE TO INTENDED SITE

$v_{NC} = v \sin\beta \approx v\beta$ COMPONENT OF v NORMAL TO r_c

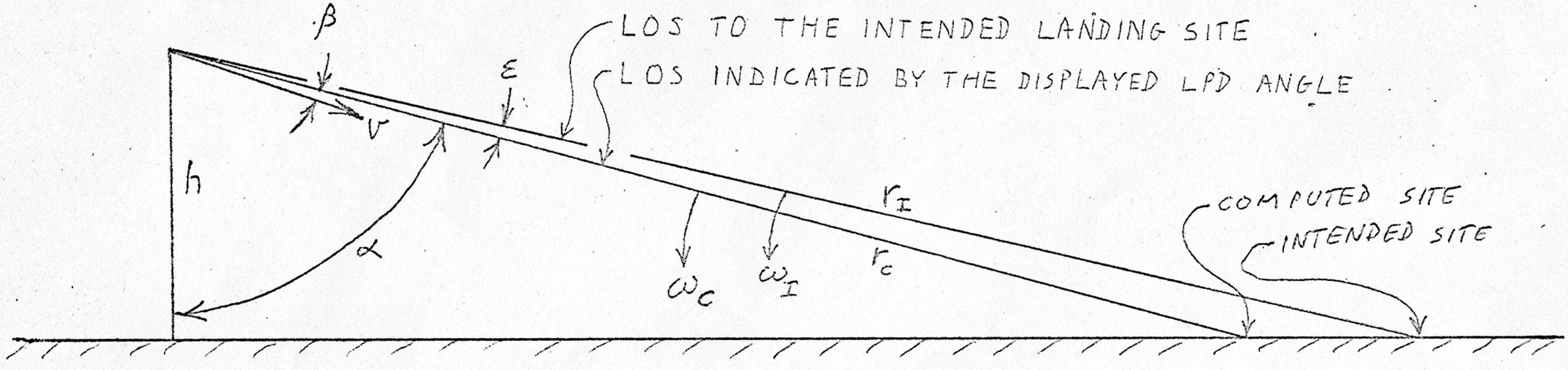
$v_{NI} = v \sin(\beta+\varepsilon) \approx v(\beta+\varepsilon)$ COMPONENT OF v NORMAL TO r_I.

$\omega_{rc} = \frac{v_{NC}}{r_c} = \frac{v\beta}{r_c}$ ANGULAR RATE OF r_c

$\omega_{rI} = \frac{v_{NI}}{r_I} = \frac{v(\beta+\varepsilon)}{r_I}$ ANGULAR RATE OF r_I

$$\frac{d\varepsilon}{dt} = \omega_{rI} - \omega_{rc} = \frac{v(\beta+\varepsilon)}{r_I} - \frac{v\beta}{r_c} = \frac{\varepsilon v + \beta v\left(1 - \frac{r_I}{r_c}\right)}{r_I} = \varepsilon \frac{v\,(1-\beta \tan\alpha)}{r_I}$$

$\frac{d\varepsilon}{dt} \approx \varepsilon \frac{v}{r}$ ASSUMING v CLOSE TO r_c AND $r \approx r_c \approx r_I$



ANALYSIS OF ANGULAR DIVERGENCE BETWEEN
THE LOS INDICATED BY THE DISPLAYED LPD ANGLE AND
THE LOS TO THE INTENDED LANDING SITE

FIGURE 2

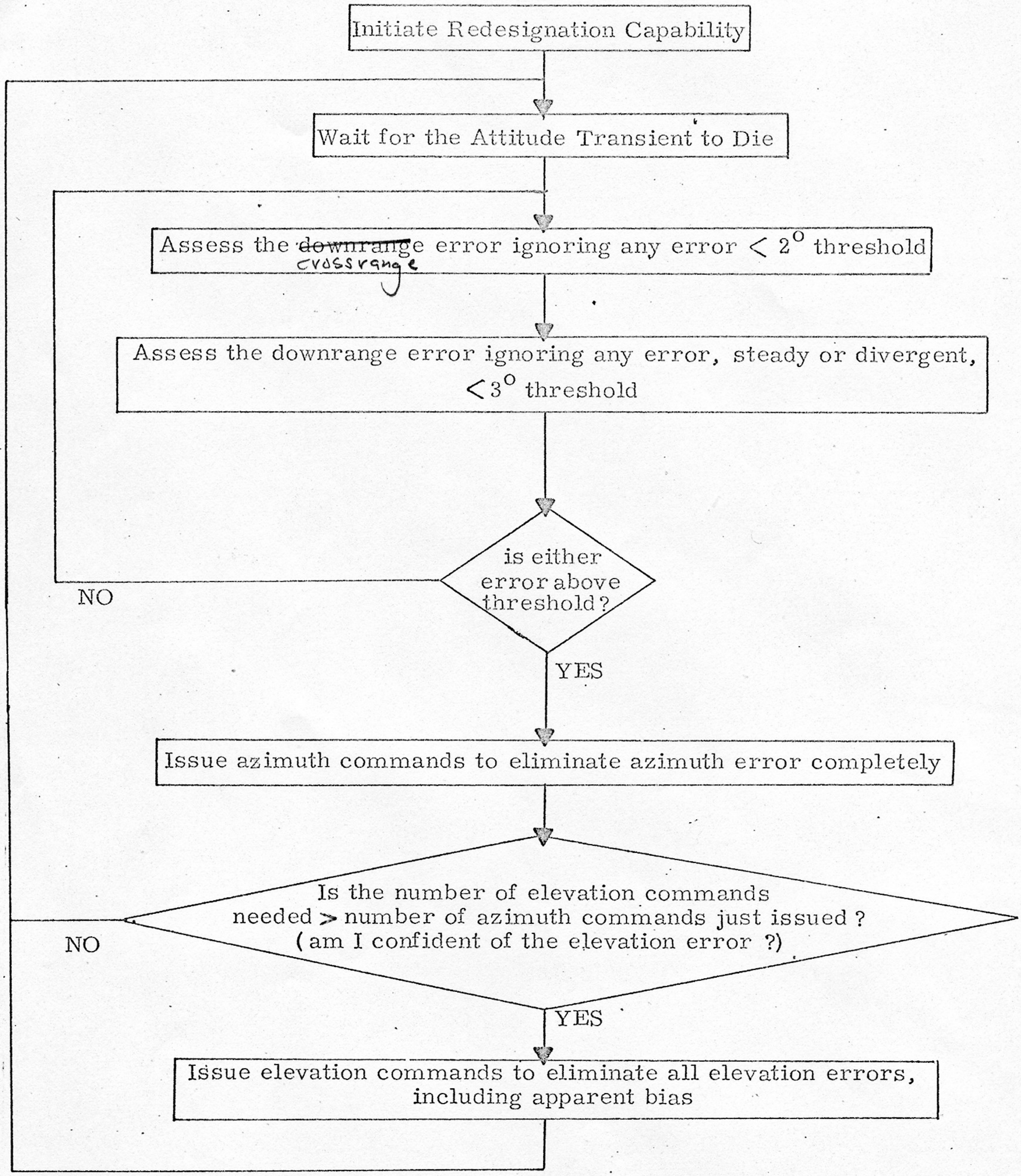


Figure 3 Landing Site Redesignation Procedure

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